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Final Report for ARO-MURI project "Tunable and reconfigurable Optical Negative-Index Materials with Low Losses"

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5b. GRANT NUMBER

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611103

6. AUTHORS
PI: Vladimir M. Shalaev

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7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Purdue University
Sponosored Program Services
Purdue University
West Lafayette, IN 47907 -2114

8. PERFORMING ORGANIZATION REPORT NUMBER

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U.S. Army Research Office
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Research Triangle Park, NC 27709-2211

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The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
Abstract
Below we highlight the most important breakthroughs and developments accomplished within this 5-year long MURI project (for a more detailed list see the annual reports):
- Negative-index metamaterials in the optical range, from near-IR to the visible have been demonstrated.
- Negative-index metamaterial with gain completely compensating losses has been demonstrated in the visible

15. SUBJECT TERMS
negative-index metamaterials (NIMs)

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Vladimir Shalaev
UU	UU	UU	UU		19b. TELEPHONE NUMBER 765-494-9855

Report Title

Final Report for ARO-MURI project "Tunable and reconfigurable Optical Negative-Index Materials with Low Losses"

ABSTRACT

Abstract

Below we highlight the most important breakthroughs and developments accomplished within this 5-year long MURI project (for a more detailed list see the annual reports):

- Negative-index metamaterials in the optical range, from near-IR to the visible have been demonstrated.
- Negative-index metamaterial with gain completely compensating losses has been demonstrated in the visible (red) part of the spectrum.
- Bulk 3D metamaterials with negative refraction have been developed.
- Negative refraction in semiconductor based metamaterials has been shown.
- Artificial metamagnetics across the entire visible part of the spectrum have been experimentally shown.
- World's smallest SPASER-based nanolaser has been demonstrated
- Nanolaser based on the hybrid gap mode confining light between a semiconductor amplifying nanostructure and a metal has been demonstrated
- Theoretical prediction and experimental realization of magnifying far-field hyperlens
- The carpet-cloak has been experimentally realized
- Tunable magnetic metamaterials have been demonstrated. We have demonstrated by theories and experiments that nonlinear and electro-optical liquid crystals may be applied in enabling tuning capabilities to metamaterials over a very broad spectral regime from the visible to the infrared. We showed that by using laser induced order parameter as a means of modifying the nematic birefringence, the switching processes can be realized at microseconds – nanoseconds speed.
- We have designed, developed, and experimentally demonstrated several novel optical switching and modulation photonics devices based on liquid crystals infiltrated nano-plasmonic structures, where the laser induced plasmonic near fields, in conjunction with applied ac filed give rise to novel optical switching, transmission and filtering operations that are not possible in passive plasmonic structures.
- It has been shown that anisotropic metamaterials can be emulated by tapered waveguides, which opens up numerous applications including cloaking
- Broadband optical cloaking using tapered waveguides have been experimentally demonstrated for the visible part of the spectrum
- The transformation optics technique was used to design a family of novel devices including an optical black-hole, a wave collimator, far-zone and near-zone focusing flat optical lenses, a right-angle bend for propagating beam fields, a three-dimensional polarization rotator, and others.
- Based on the transformation optics approach, we demonstrate that a microlens may act as a two-dimensional fish-eye or an inverted Eaton lens. An asymmetric inverted Eaton lens may exhibit considerable image magnification, which has been confirmed experimentally.
- The singular photonic density of states in hyperbolic metamaterials has been predicted; first preliminary experiments support the theory
- We demonstrated that metamaterials with hyperbolic dispersion (h-MMs) can be used to study metric signature transitions and the cosmological "Big Bang".
- A theory for basic nonlinear optical processes in NIMs and in double-domain positive/negative-index metamaterials has been developed. This includes optical parametric amplification, bistability, second-harmonic generation, novel solitons, etc. Light pulse dynamics in NIMs in the presence of losses and amplification and extremely short pulse propagation in nonlinear NIMs have been studied. Loss compensation with NL amplification has been shown.
- Resonant field-enhancement phenomena and universal energy absorption at the interface n=0 for a material with a refraction index n passing through n=0 continuously, was discovered.
- Metamaterials based on Si photonic crystals (PhCs) have been developed
- We have demonstrated mechanically tunable photonic crystal lens.
- The field of optical metamaterials has been linked to that of celestial mechanics, thus opened the way to investigate light phenomena reminiscent of orbital motion, strange attractors and chaos, in a controlled laboratory environment.
- Experimental observation of nonlinear negative refraction at optical frequencies using four-wave mixing (4WM), wherein the incident and negatively refracted beams are at different frequencies, fully fulfilling the Snell's law.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

The project participants had numerous presentations on their work on the project which includes 97 presentations in total which were invited, keynote, or plenary.

Number of Presentations: 97.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received	Paper

TOTAL:

Patents Submitted

1. C. Khoo and D. Werner, “Liquid crystal containing core-shell nano-spheres for reconfigurable optical-, infrared- and Terahertzfrequency
negative and zero index materials.” PSU Invention Disclosure #2006 -3217. Filed June 8, 2006 [Army and NSF].
2. “Flat transformational electromagnetic material lenses for near-field and far-field focusing applications” byD. H. Werner and D.-H.Kwon
3. “Elimination of coupling and interference between antennas in multi-standard multi-antenna systems and methods thereof” by D. H.
Werner and D.-H. Kwon
4. A.V. Kildishev and V. M. Shalaev, Engineering Space for Light with Transformation Optics.

Patents Awarded

Awards

- Shalaev received the 2010 Max Born Award of the Optical Society of America, in recognition of his seminal contributions to both the theoretical framework and the optical realization of optical metamaterials.
- Shalaev received the 2010 Willis E. Lamb Award for Laser Science and Quantum Optics
- Prof. Xiang Zhang, SPIE Fellow
- Muralidhar Ambati (Berkeley), Materials Research Society (MRS) Graduate Student Silver Medal
- Yongmin Liu, SPIE Scholarship Award
- V. M. Shalaev – 2009 McCoy Award for best scienitific achievement at Purdue University
- X. Zhang – OSA Fellow
- Zhang became a Member of National Academy of Engineering
- Shalaev became a Fellow of the Institute of Electrical and Electronic Engineers (IEEE)
- Shalaev became Robert and Anne Burnett Distinguished Professor of Electrical and Computer Engineering, Purdue University – since 2011
- Shalaev received the Nanotechnology Award from UNESCO
- D. Werner received the IEEE Antennas and Propagation Edward E. Altshuler Prize Paper Award for the following publication: “Do-Hoon Kwon and Douglas H. Werner, “Transformation Electromagnetics: An Overview of the Theory and Applications,” IEEE Antennas and Propagation Magazine, 52 (1), pp. 24-46, February (2010).
- Xiang Zhang, Fred Kavli Distinguished Lectureship in Nanoscience, 2011 Materials Research Society (MRS) Spring Meeting.
- Xiang Zhang, Miller Professorship, UC Berkeley, 2011
- Xiang Zhang, Distinguished Visiting Scientist (DVS), the Institute of Optical Sciences, University of Toronto, 2011
- Xiang Zhang, CESASC 2011 Achievement Award, The Chinese-American Engineers and Scientists Association of Southern California (CESASC), 2011
- Narimanov became a Fellow of the Institute of Electrical and Electronic Engineers (IEEE)

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Chettiar	0.25	
Cai	0.25	
Yuan	0.25	
Kennedy	0.25	
Xiao	0.25	
Alekseev	0.25	
Jacob	0.25	
Ambati	0.25	
Valentine	0.25	
Liou	0.25	
Ma	0.25	
Wu	0.25	
Tamma	0.25	
Bayraktar	0.50	
Kim	0.25	
Chen	0.25	
Ishii	0.25	
W. Chen	0.25	
Koswatta	0.25	
Liu	0.25	
Pennybacker	0.25	
Borneman	0.25	
Stinger	0.25	
Park	0.25	
Joshi	0.25	
Dudley	0.25	
Kudyshev	0.25	
Tamma	0.25	
FTE Equivalent:	**7.25**	
Total Number:	**28**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Kolchin	1.00
P. Zhang	0.50
T. Zentgraf	0.50
U. Cui	0.50
Korotkevich	0.50
S. Zhang	1.00
Y. Sivan	0.25
FTE Equivalent:	**4.25**
Total Number:	**7**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Shalaev	0.10	
Zhang	0.10	
Narimanov	0.10	
Khoo	0.10	
Werner	0.10	
Indik	0.10	
Park	0.10	
FTE Equivalent:	**0.70**	
Total Number:	**7**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
M. Swanson	0.25	ECE
FTE Equivalent:	**0.25**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	1.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:	1.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:	1.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):	1.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	1.00

Names of Personnel receiving masters degrees

NAME
B. Kennedy
P. Kaswatta
X. Ni
R. Bakker
W. Chen
Total Number: **5**

Names of personnel receiving PHDs

NAME
Z. Liuy
S. Xiao
J. Borneman
Z. Jacob
M. Liu
J.Y. Kim
K.P. Chen
M. V. Stinger
Total Number: **8**

Names of other research staff

NAME	PERCENT_SUPPORTED
A. Kildishev	0.25
V. Drachev	0.20
Diaz	0.50
FTE Equivalent:	**0.95**
Total Number:	**3**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

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Technology Transfer

Final Report

Publication and Presentation Summary

Proposal Number: 50342-PH-MUR,

Agreement Number: W911NF-06-1-0377

Papers Published in Peer Reviewed journals

The total number of papers published in peer-reviewed journals is 160. This includes the 24 paper below publications in the high-profile journals Science, Nature, Nature Materials, Nature Photonics, Nature Communcation, Nature Physics, and Physical Review Letters::

1. E.E. Narimanov and V.M. Shalaev, Beyond diffraction, NATURE, Vol. 447, pp.266-7(2007).
2. Wenshan Cai, Uday K. Chettiar, Alexander V. Kildishev & Vladimir M. Shalaev, Optical cloaking with metamaterials, Nature Photonics, VOL 1, PP 224-27 (2007)
3. Shalaev V.M., Optical negative-index metamaterials, Nature Photonics, v.1, 41-48 (2007).
4. Zhaowei Liu, Hyesog Lee, Yi Xiong, Cheng Sun and Xiang Zhang, "Far-Field Optical Hyperlens Magnifying Sub-Diffraction-Limited Objects", Science, 315, 1686, 2007
5. Natalia M. Litchinitser, Ildar R. Gabitov, Andrei I. Maimistov, Bistable PIM-NIM Coupler , PRL, 99(7), 2007
6. V. A. Podolskiy and E. E. Narimanov, Phys. Rev. Lett. 98, 179401 (2007)
7. Jason Valentine, Shuang Zhang, Thomas Zentgraf, Erick Ulin-Avila, Dentcho A Genov, Guy Bartal and Xiang Zhang, “Three Dimensional Optical Metamaterial Exhibiting Negative Refractive Index”, Nature (published in August, 2008)
8. N.M. Litchinitser, I.R. Gabitov, A.I. Maimistov, Optical Bistability in a Nonlinear Optical Coupler with a Negative Index Channel, PRL, 99, 113902 (2007)
9. A. J. Hoffman, L. Alekseyev, S. S. Howard, K. J. Franz, D. Wasserman, V. A. Podolskiy, E. E. Narimanov, D. L. Sivco, C. Gmachl, "Negative refraction in semiconductor metamaterials," Nature Materials 6, 946 (2007)
10. J. Yao. Z. Liu, Y. Wang, C. Sun, G. Bartal, A. M. Stacy, and Xiang Zhang, Optical Negative Refraction in Bulk Metamaterials, Science (published in August, 2008)
11. Igor I. Smolyaninov, Vera N. Smolyaninova, Alexander V. Kildishev, and Vladimir M. Shalaev, Anisotropic Metamaterials Emulated by Tapered Waveguides: Application to Optical Cloaking, PHYSICAL REVIEW LETTERS, VOL 102, 213901-4 (2009):
12. Natalia M. litchinitser and Vladimir M. shalaev, Loss as a route to transparency, Nature Photonics, vol. 3, pp. 75-6 (2009).
13. Vladimir M. Shalaev, Transforming Light, SCIENCE, VOL 322, pp. 384-86 (2008).
14. E. Narimanov, "Photonics: Metamaterials to beat the static", Nature Materials 7, 273 - 274 (2008)
15. M. A. Noginov, G. Zhu, A. M. Belgrave, R. Bakker, V. M. Shalaev, E. E. Narimanov, S. Stout, E. Herz, T. Suteewong & U. Wiesner, "Demonstration of a spaser-based nanolaser", Nature 460, 1110 (2009)

16. Dentcho A. Genov, Shuang Zhang and Xiang Zhang, "Mimicking celestial mechanics in metamaterials" Nature Physics, published online, 2009
17. Atsushi Ishikawa, Shuang Zhang, Dentcho A. Genov, Guy Bartal, and Xiang Zhang, "Deep Subwavelength Terahertz Waveguides Using Gap Magnetic Plasmon" Physical Review Letters, Vol.102, 043904, 2009
18. Jason Valentine, Shuang Zhang, Thomas Zentgraf, Erick Ulin-Avila, Dentcho A Genov, Guy Bartal and Xiang Zhang, "Three Dimensional Optical Metamaterial Exhibiting Negative Refractive Index", Nature, Vol.455, 376, 2008
19. Shumin Xiao, Vladimir P. Drachev, Alexander V. Kildishev, Xingjie Ni, Uday K. Chettiar, Hsiao-Kuan Yuan, and Vladimir M. Shalaev, Loss-free and active optical negative-index metamaterials, Nature 466, 735-738 (2010)
20. .I. Smolyaninov, E. E. Narimanov, "Metric Signature Transitions in Optical Metamaterials", *Phys. Rev. Lett.* **105**, 067402 (2010)
21. Y. Gao, J. P. Huang, Y. M. Liu, L. Gao, K. W. Yu, and X. Zhang, "Optical Negative Refraction in Ferrofluids with Magnetocontrollability", *Physcial Review Letters*, Vol. 104, 034501, 2010.
22. W. Cai and V. M. Shalaev, Into the visible, Physics World 24 (7), 30-34 (2011).
23. S.C. Kher, Y.M. Liu, L.W. Martin, P. Yu, M. Gajek, S.-Y. Yang, C.-H. Yang, M.T. Wenzel, R. Jacob, H.-G. von Ribbeck, M. Helm, X. Zhang, L.M. Eng, and R. Ramesh, "Near-field examination of perovskite-based superlenses and superlens-enhanced probe-object coupling", ***Nature Communications***, Vol. 2, 249
24. S. Palomba, S. Zhang, Y. Park, G. Bartal, X. Yin, X. Zhang, Optical Negative refraction by four-wave mixing in thin metallic nanostructures, Narure Materials, DOI:10.138/NMAT3148, published on line 30 October 2011.

Conference Proceedings and non Peer Reviewed and Papers;

There are 95 papers, in total, published in conference proceedings and non-peer reviewed journals

Books
Two books are published.
Chapter Books:

There 16 book chapters published.

Presentations:

The project participants had numerous presentations on their work on the project which includes 97 presentations in total which were invited, keynote, or plenary.